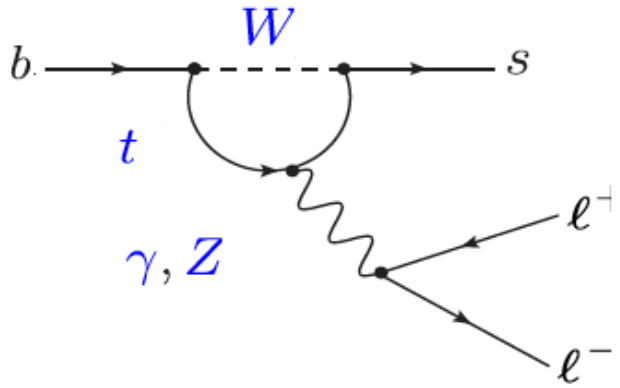
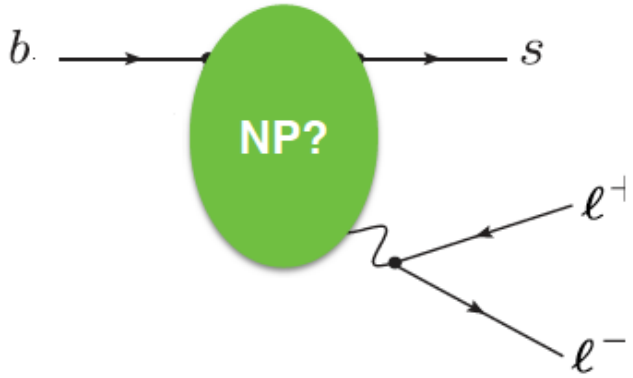
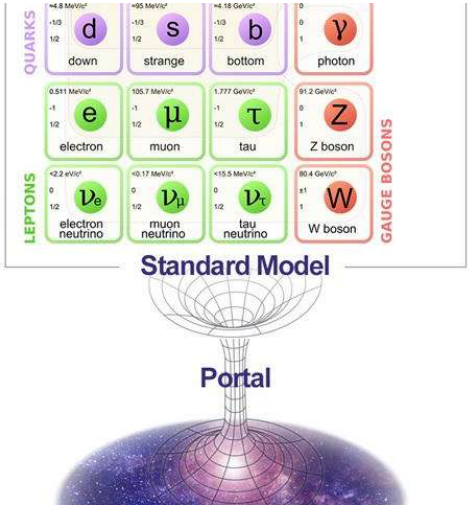
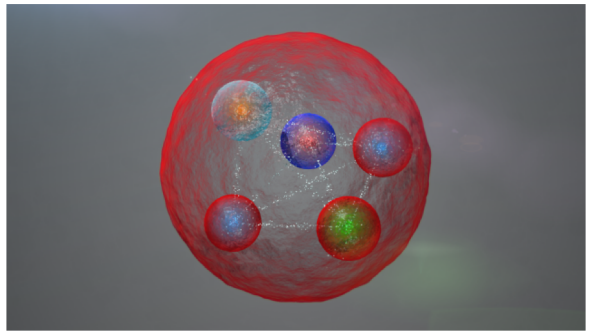




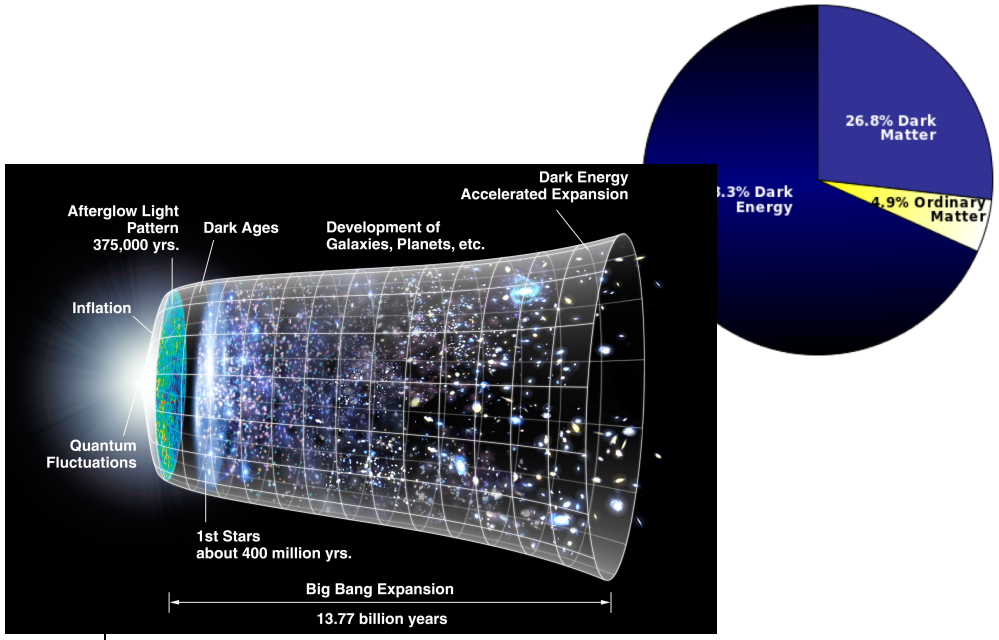
Rare Processes and Precision Measurements Frontier Kick-off meeting Introductory remarks

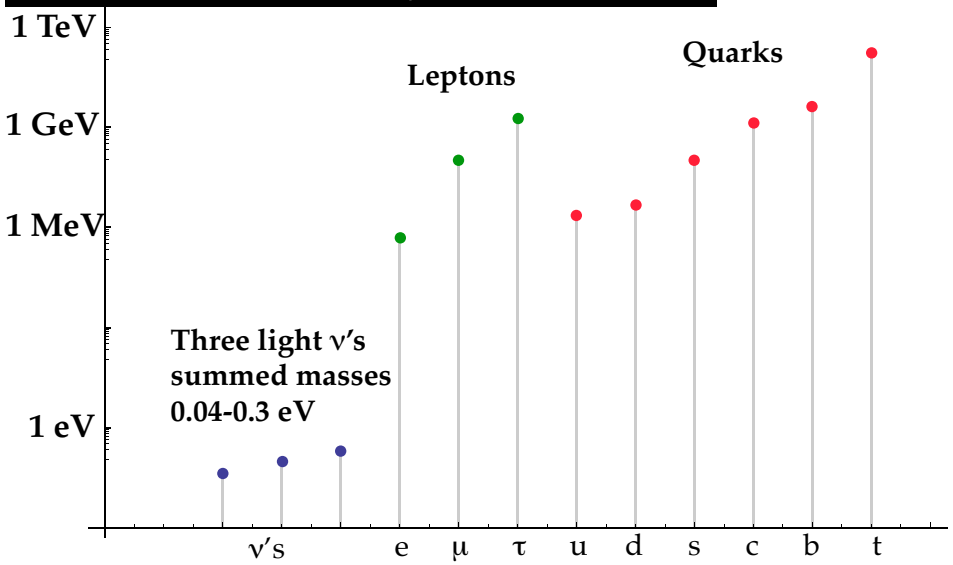


Marina Artuso, Bob Bernstein, Alexey Petrov



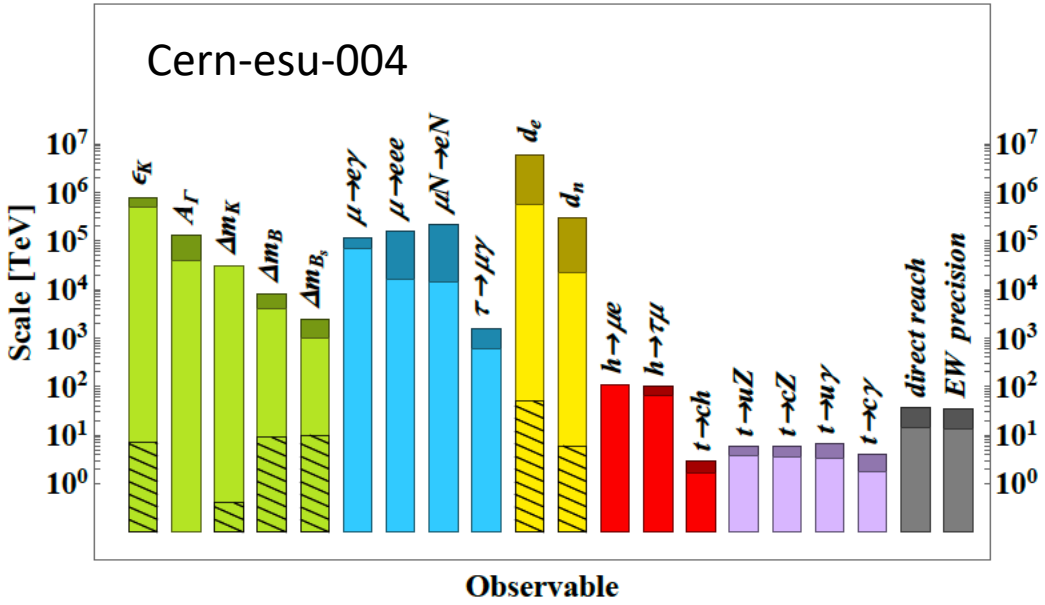
The big questions





1. What is the nature of the majority of matter composing the universe?
2. What is the CP violation mechanism underlying the matter-dominated universe that we can see today?
3. What is the origin of the mass hierarchy of fundamental particles?
4. Which is the nature of the new physics beyond the Standard Model?
5. What is the architecture of particles composed of tightly bound quarks?

Our study is linked on one the P5 science drivers:



Significant advances in this global program (Belle II is taking data, LHCb installation in progress, Mu2e….) provide a solid foundation to plan next decade and beyond.

Detecting the quantum influence of new particles: The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena. There are many examples of such experiments taking place in Europe, Japan, China, and the U.S. The global program includes projects that are complementary to one another using different kinds of particles as probes that are sensitive to different types of new particles and interactions. Some notable examples involve a revolutionary increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus Mu2e (Fermilab) and COMET (J-PARC), further studies of rare processes involving heavy quarks or tau leptons at Belle II (KEK) and LHCb (LHC), and a search for proton decay using the large neutrino detectors of the LBNF and proposed Hyper-K experiments.

Input from the European Strategy

European Strategy Update

2020 Strategy Statements

4. Other essential scientific activities for particle physics

Diverse science at low energy: exploration of dark matter and flavour puzzle

- Change of paradigm for dark matter particles - could be as light as 10^{-22} eV to as heavy as primordial black holes of $10 \times M_{\odot}$
- Observed pattern of masses and mixings of quarks and leptons, remains a puzzle
- Physics Beyond Colliders study identified many high impact options with modest investment
- Larger scale new facilities such a the Beam Dump Facility, and later LHeC option at CERN, difficult to resource within the CERN budget, considering the other recommendations of this Strategy
- Improvements in the knowledge of the proton structure needed to fully exploit the potential of present and future hadron colliders - added value from fixed target experiments and from Electron Ion Collider (CD0) in BNL
- Given the challenges faced by CERN in preparing for the future collider, the role of the National Laboratories in advancing the exploration of the lower energy regime cannot be over-emphasised (ex. axions at DESY, rare muon decays in PSI, dark photon in Frascati)

a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. *Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.*

Overview of next decade from RPF

Illustrative not comprehensive

- High level view of what is or may be coming
- Collected input from TG Conveners
- You'll hear about these during the day
- Remarks illustrate the richness of the physics, complete landscape will emerge from our work and your **LOI/Contributed papers**
- We will consider:
  - Some experiments are poised to start data taking (e.g. LHCb upgrade, Mu2e,…) others have just started their physics program (e.g. Belle II..)
  - Major upgrades & new initiatives that need to be planned now!

Theoretical issues of rarity and precision

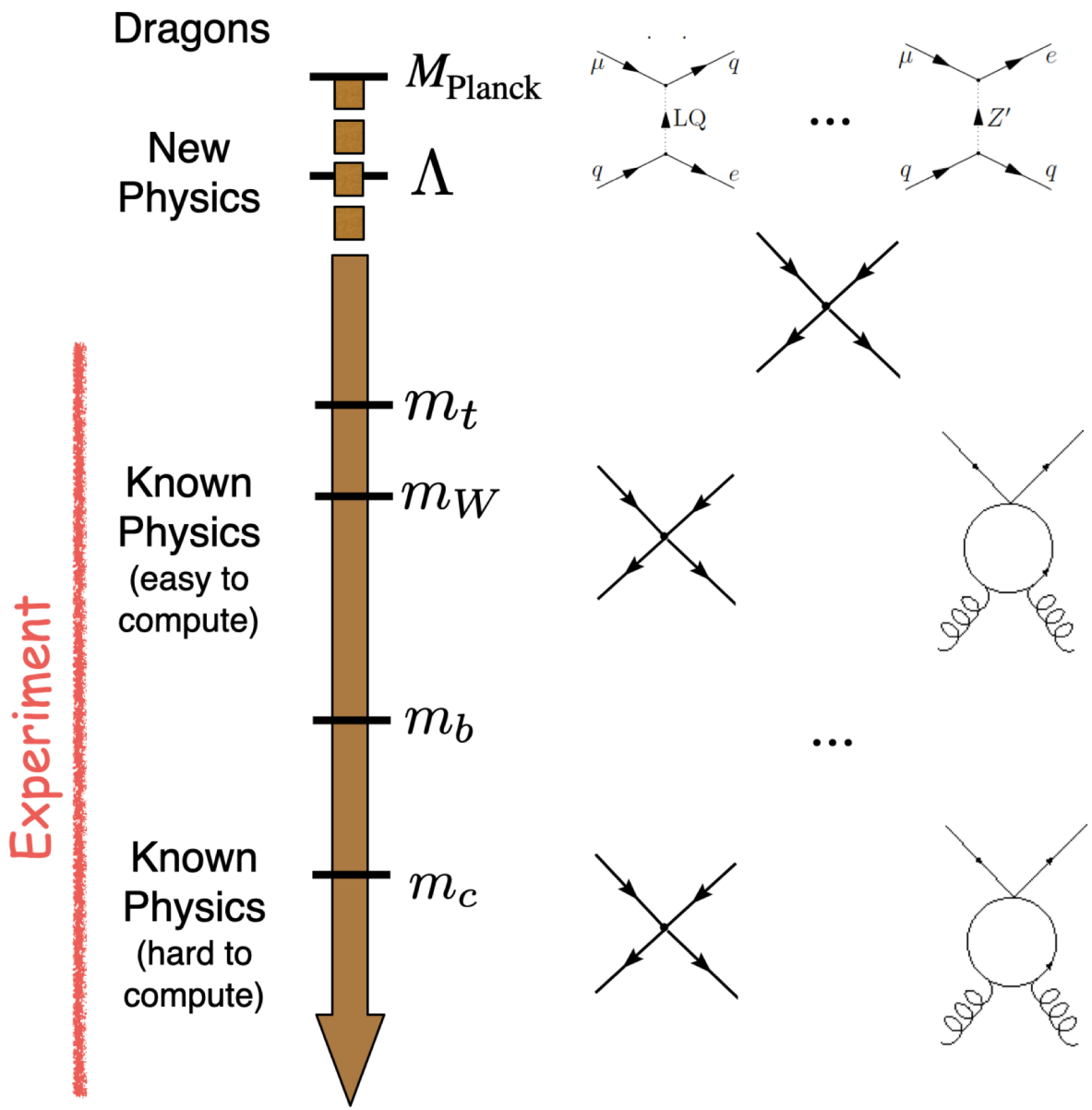
- Why do we believe there are still new particles to discover?
  - Baryogenesis (B&L-violation, CP-violation), dark matter, neutrino masses? Gravity?
  - Flavor problem, hierarchy problem, cosmological constant
  - Strong CP problem?

- Glorious past of direct High Energy searches (before Higgs)
  - General arguments (unitarity) told us that the Standard Model is not complete
  - General arguments (unitarity) told us where to search for Higgs or New Physics
    - This is not so anymore. Any hints?

- Glorious past of Precision Studies
  - GIM mechanism: before top quark discovery: $\Delta m_B \sim m_t^2$
  - Electroweak precision measurements: $\sim \log m_H^2$

    - New particles in radiative corrections? Power suppressed effects? Fine tuning?
    - Studies of manifestations of discrete symmetries breaking?

Heavy New Physics states: SM EFT



- SM EFT features
  - Scale separation (good for computations)
  - Almost infinite number of NP models matches into a finite number of SM EFT effective operators
  - SM is the leading "term" in this expansion: renormalizable theory with no intrinsic scale which tells us where it breaks down

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

  - Note: dim-odd operators are B or L – violating, dim-even are both B or L violating and conserving (ν: Majorana mass dim 5; proton decay: dim 6, …) RF-04
  - Flavor-violating transitions: best places to search? RF-01,02,05

- Low energy: soft QCD troubles
  - Models or numerical computations (lattice, QCD SR..)
  - In some cases enhanced symmetries lead to model-independent predictions (HQET, SCET, χPT, …)
  - Leads to rich structures in spectroscopy RF-07

Light New Physics states: models

- Possible new undiscovered light states RP-06
  - Proposed as both need-based (axion) and just-so (dark photon) approaches
  - Tiny couplings to SM sector: excellent DM candidates

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \mathcal{L}^{(4)}_{\text{portal}} + \mathcal{L}^{(5)}_{\text{portal}} + \mathcal{L}^{(6)}_{\text{portal}} + \ldots$$

  - Several ways of coupling to SM (portals)

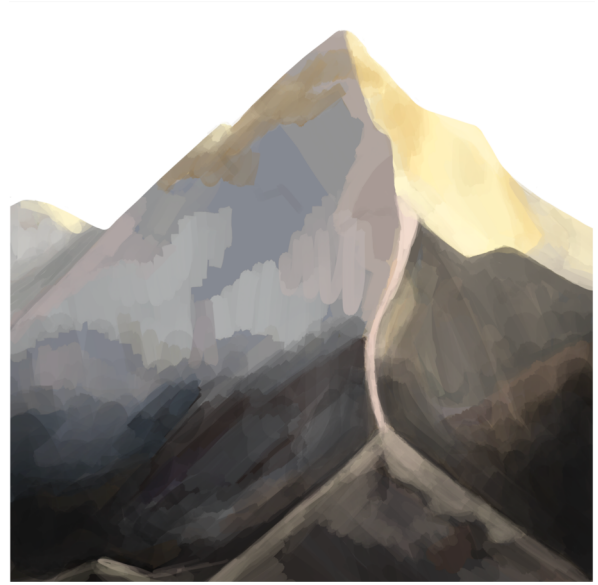
$$\mathcal{L}_{Higgs} = \epsilon_H^S \left(H^\dagger H\right) |S|^2 + \epsilon_H^V \left(H^\dagger H\right) V_\mu V^\nu$$

Dim-4:

$$\mathcal{L}_{neutrino} = \epsilon_\nu \left(\bar{L} H\right) \psi$$

$$\mathcal{L}_{vector} = -\frac{\epsilon_V}{2} V_{\mu\nu} F^{\mu\nu}$$

Dim-5: “hidden valleys” (large scale suppression)



  - Can be studied at both flavor factories and dedicated expts.

Experiments Over Next Decade

- Precision tests of SM parameters and search for new physics with the study of strange and light quarks (TG2)
  - Rare Kaon Processes: $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^o \nu\bar{\nu}$ (TG2)
    - NA62 (CERN) 2021-2024, 10% on $K^+ \to \pi^+ \nu\bar{\nu}$
    - Upgrade to facility at CERN, 5% on K^+, 20% on K_L at SM
    - KOTO (J-PARC) $K_L \to \pi^o \nu\bar{\nu}$ at SM, x10 with upgrades
    - Rare K decays studied at LHCb
  - REDTOP, JEF proposals for η, η' factories

- Charged Lepton Flavor Violation (TG5)
  - Muons (end of 2020's): mass scales of 10^3-10^4 TeV with discovery experiments
    - Mu2e, COMET: $\mu^- N \to e^- N$ and $\mu^- N \to e^+ N(Z-2)$ to 10^{-17}
    - MEG-II: $\mu \to e\gamma$, x10 improvement taking data soon and upgrades considered at PSI
    - Mu3e: $\mu \to eee$, staged
  - Taus: BR(10^{-9}) in many modes
    - LHC: x10 improvements
    - BELLE-II: x10 improvement in limits in many channels
    - Super Tau Charm Factory proposals
    - Tau LFV proposal (noted by European Strategy Group)

Experiments over Next Decade

- “Fundamental Physics” (TG3)
  - EDMs
    - nEDM x10-x100 to 1e-28 e-cm (SNS)
    - Interesting possibilities for charged EDMs in storage rings, possibly muons as well?
  - Experiments with anti-protons at CERN:
    - Hyperfine structure of antihydrogen (ASACUSA, ALPHA) and antiprotonic helium (ASACUSA) with spectroscopy
    - Basic properties of the anti-proton (BASE)
    - Gravitational effects on antimatter (GBAR, AEgIS, ALPHA-g)

- Dark sector at (TG6)
  - Many new proposals and active programs in existing experiments: in US, LDMX; CODEX-B, LHCb, JEF, Mathusla, SHiP, TauFV, KLEVER (TG2!),…too many great ideas to name and very different investments required! Active programs also at LHCb and Belle II.
  - See https://cds.cern.ch/record/2652223/plots

Experiments over Next Decade

- Hadron Spectroscopy (TG7)
  - Already quite a rich spectroscopy with potentially exotic binding pattern: new structures of QCD-bound assemblies besides (qqq) and ($q\bar{q}$)?
  - Confirm existence of hadrons with QCD glue as valence components: "hybrid" mesons and "glueballs"
  - Validate lattice QCD with baryon and meson spectroscopy & understand QCD in non-perturbative regime
  - The experiments: LHCb, Belle, BES III (charm) and low energy measurements (GLUEX..)

- B and c weak decays (TG1)
  - Find signatures of new physics in beauty and charm decays
  - Precision tests of the Standard Model: V_{cb}, V_{ub}, the angle γ, unitarity triangle tests…
  - The key experiments are going to be LHCb and Belle II, studies on charm decays at BESIII
  - Selected final states involving μs will be studied at HE frontier experiments
  - Proposals for super tau charm factories at Novosibirsk and Hefei

Experiments over Next Decade

- BLV (TG4) :
  - 0nDBD:
    - the next decade will see (in the US) the tonne-scale program (DoE-NP)
    - in between, results from: Kamland2-Zen, SNO+, NEXT-100, Legend-200, Cuore, smaller scale efforts
  - Proton decay
    - JUNO, DUNE, Hyper-K
  - n-nbar (lots of enthusiasm here!)
    - Oak Ridge development, ESS
    - DUNE
    - results from SuperK
  - See https://indico.fnal.gov/event/44268-70

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Upcoming Facilities/Upgrades in next Decade

- LHCb Upgrades
  - Upgrade 1a should start taking data at the beginning of 2022. It expects to reach ~50 fb^{-1} [luminosity x5, software trigger with data pushed out of the detectors in real time].
  - Upgrade 1b tracking upgrades: better downstream tracking and tracking chambers in the magnet ⇒much improved efficiency for low momentum tracks (and thus multi-body hadron decays, $D^* \to \pi D^0$…)
  - Upgrade II (currently Framework TDR being produced, see LHCb-PUB-2018-009: luminosity x7.5, new calorimeter to study channels with γ, π^0 in the final state.
  - Rich physics program across many topical groups:
    - Rare decays
    - Precision test of the SM and possible tensions (V_{cb},V_{ub},gamma) measured with loop and tree-mediated processes, CP violation in B and Charm decays)
    - Dark sector (dark photons, higgs portals) and exotic dark matter in b-decays
- PIP-II at FNAL
  - ~1 MW available for rare and precision measurements
  - New muon program ideas developing at this Snowmass
    - CLFV: all muon channels in new facility at PIP-II, x100 better than current upgrades
      - Group forming from US, EU, Japan with multiple linked LOIs being written
    - Muonium-antimuonium oscillations; muon EDMs becoming interesting?